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KIC SIZE EFFECT STUDY ON TWO HIGH-
STRENGTH STEELS USING NOTCHED BEND
SPECIMENS

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K_{IC} SIZE EFFECT STUDY ON TWO HIGH-STRENGTH STEELS USING

NOTCHED BEND SPECIMENS

INTRODUCTION

The work reported here is part of a study for NASA entitled "Evaluation of High Toughness Materials". Earlier phases involved the characterization of a 10% Ni quenched and tempered steel and weldments of it, particularly with respect to its fracture toughness (1). Confirming earlier reports, it was found to be a very tough material, justifying anticipated difficulty in measuring the plane strain fracture toughness with specimens of practical size. To address this problem, this phase provides for K_{IC} tests on the base plate in a series of specimen sizes, starting with full plate thickness, then to subscale specimens surely too small to meet the established size criteria. For comparison, a similar size group of specimens was prepared of a common low alloy Q&T steel, tempered so as to leave a lower (140ksi) level of tensile yield strength. With this data base, in the form of load versus notch-opening records, various schemes for analyzing the undersize specimen records could be attempted to estimate the full-size specimen value of K_{IC} . The results of such attempts are reported here.

- (1). F. R. Stonesifer and H. L. Smith, "Characterization of GTA Weldments in 10Ni-8Co-2Cr-1Mo Steel", NRL Memorandum Report 2466, June 1972.

Manuscript submitted October 16, 1974.

MATERIAL

The 10%Ni material of nominal composition, 10Ni-8Co-2Cr-1Mo, was from a three-inch plate from U. S. Steel Corporation heat No. C51363. This steel was manufactured by the Basic Open Hearth method, vacuum-induction melted, vacuum-arc remelted, cold rolled, double austenitized, and aged. The austenitizing cycle consisted of a 180 minute hold at 815°C followed by quenching in agitated cool water. Aging was at 950°C for 10 hours. The resulting 0.2% offset yield strength was about 180 ksi.

The low alloy steel was AISI 4340 of nominal composition, 40C-70Mn-1.8Ni-80Cr-25Mo, from a commercial grade, three-inch plate produced by Benedict-Miller, Inc. from heat no. A1707-7B. The plate was heat treated and drawn back to obtain a yield strength of about 140 ksi.

SPECIMEN PREPARATION

Figure 1 shows the specimen configuration with dimensions given in terms of the specimen depth, W . Three identical specimens were machined from each of the two materials with beam depths, W , of six, five, and four inches. The halves of these broken specimens were then used to machine specimens with depths of three, two, and one inch.

Valid K_{Ic} values were estimated before testing so that the fatigue precracking loads could be determined for each specimen size and material. These loads were determined such that the K_f (max) would at no time exceed 60 percent of K_{Ic} , and at the finishing load $K_f(\text{max})/E$ would not exceed $0.002 \text{ in}^{\frac{1}{2}}$. Therefore the listed (see Table 1) maximum load was not exceeded at any time, and the finishing load was not

exceeded during growth of the last 2.5% of the total initial crack length.

TEST RESULTS AND ANALYSIS

Standard ASTM 0.505" tensile specimens were tested to obtain the tensile properties, tabulated in Table 2. The notched bend specimens were tested in simple three-point bending over a span of $4W$ essentially as prescribed in ASTM test method E399 (2).

The various sized fracture toughness precracked specimens were loaded to failure in a closed-loop controlled testing machine. The output from an E399 type clip gage in the specimen notch was recorded on the x-axis of an x-y plotter. The load cell output plotted on the y-axis completed the load-displacement record. K_Q values were calculated from the formula in the E399 standard method using various values of load and a/w .

Five values of K_Q were calculated for each specimen. Three of these calculations were based on the actual measured crack length and loads read directly from the load-displacement record. The other two calculations involved use of an effective crack length which is the measured crack plus an additional allowance for the plastic zone.

The 5% secant loads were determined by the intersection of the load-displacement curve with a secant line drawn through the origin with a slope 95% of that for the initial linear portion of the record. This process is illustrated in E399. The maximum load is simply taken as the ultimate load on the load-displacement record.

- (2). "Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials", E399, ASTM Standards, Part 31, 1972, pp. 955-974.

K_Q values calculated from the 5% secant and the maximum loads were then "corrected" by the graphical method as proposed by Kies (3). A "corrected" a/w is determined by the intersection of a line of slope S , passing through the measured a/w and the $f(a/w)$ curve. (The limit of solvability for this method is reached when the two curves become tangent). General formulas for $f(a/w)$ and S are given in Figure 2. More details of this method can be obtained in the referenced report.

The "scaling correction" was proposed by Stonesifer and Smith (4). This method adds a plasticity correction to the load rather than to the crack length. Figure 3 illustrates how the corrected load is obtained. This method is based on total deflection at maximum load and the elastic modulus of the material. The corrected load is presumably the load that would have been obtained had the specimen not plastically deformed but remained elastic to the same level of strain.

The average values of K_Q calculated by each of the five methods are shown in Table 3 for every specimen size and material. These values are then shown plotted in Figures 4 and 5. A successful correction method would be expected to show a constant K_Q that is independent of specimen size.

- (3). J. A. Kies, H. L. Smith, and F. R. Stonesifer, "Graphical Methods for Plasticity Corrections in Fracture Mechanics", NRL Report 6918, September 18, 1969.
- (4). F. R. Stonesifer and H. L. Smith, "Characterization of TIG Welds in 12-5-3 Maraging Steel Plate With Application of a New Scaling Method for K_{IC} Plasticity Corrections", NRL Report 7053, April 16, 1970.

Using the 5% secant K_Q for the six-inch specimens in the E399 size requirement, one finds that a minimum dimension of 2.64 inches is required for the 10% Ni alloy or 2.28 inches for the 4340 steel. Therefore specimen depths of twice this amount, or 5.28 and 4.56 inches would be required for valid K_{Ic} determinations for these two materials.

CONCLUSIONS

None of the methods tried for predicting valid K_{Ic} values from sub-sized specimens seemed to be completely satisfactory for these two materials. From these data one might conclude that the best method would be that of using the maximum tensile load. This method assumes no sub-critical crack growth prior to failure.

Several new approaches to the problem have been recently developed which may be more successful. Two such developments have been the J-integral (5) and the equivalent energy (6) methods. These later methods require additional test data not presently available for the specimens tested in this study.

- (5). J. R. Rice, "Mathematical Analysis in The Mechanics of Fracture" Fracture, Vol. 2, Chapter 3, pp. 191-311.
- (6). J. N. Robinson, A. S. Tetelman, "Comparison of Various Methods of Measuring K_{Ic} on Small Precracked Bend Specimens That Fracture After General Yield", UCLA-ENG-7409, January 1974.

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- (1). F. R. Stonesifer and H. L. Smith, "Characterization of GTA Weldments in 10Ni-8Co-2Cr-1Mo Steel", NRL Memorandum Report 2466, June 1972.
- (2). "Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials", E399, ASTM Standards, Part 31, 1972, pp. 955-974.
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- (6). J. N. Robinson, A. S. Tetelman, "Comparison of Various Methods of Measuring K_{IC} on Small Precracked Bend Specimens That Fracture After General Yield", UCLA-ENG-7409, January 1974.

TABLE 1: FATIGUE PRE-CRACK LOADS

Specimen Depth W (in.)	Test Span (in.)	10% Ni Steel $\sigma_y \approx 180 \text{ ksi}; K_{IC} \approx 200 \text{ ksi}/\text{in.}$		4340 Steel $\sigma_y \approx 140 \text{ ksi}; K_{IC} \approx 140 \text{ ksi}/\text{in.}$	
		Maximum Load (lbs.)	Finishing Load (lbs.)	Maximum Load (lbs.)	Finishing Load (lbs.)
1	4	5,760	1,730	4,040	1,730
2	8	16,200	4,860	11,400	4,860
3	12	30,000	9,000	21,000	9,000
4	16	46,100	13,800	32,300	13,800
5	20	63,100	18,900	44,200	18,900
6	24	85,700	25,700	60,000	25,700

TABLE 2 TENSILE PROPERTIES

Material Property	Material	
	10% Ni Steel	4340 Steel
0.2% Offset Yield Stress (ksi)	183.1	139.8
Ultimate Yield Stress (ksi)	190.1	156.2
Young's Modulus ($\times 10^6$)	28.3	29.8
Reduction in Area (%)	68.2	45.3
Elongation over 2" gage length (%)	17.5	15.3

Note: Each value is average of 3 tests.

TABLE 3: COMPARISON OF K_Q VALUES CALCULATED BY VARIOUS METHODS

Material	10% Ni Steel						K_Q (ksi $\sqrt{\text{in.}}$)						4340 Steel					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Specimen Depth (in.)																		
K_Q based on 5% secant load	110.8	159.0	171.9	172.8	166.6	188.0	97.6	116.8	115.8	126.1	130.5	133.5	97.6	116.8	115.8	126.1	130.5	133.5
K_Q based on 5% secant load with Graphical Correction	118.3	171.1	181.2	179.4	171.3	193.4	107.2	124.9	120.6	130.4	134.4	136.7	107.2	124.9	120.6	130.4	134.4	136.7
K_Q based on Maximum load	176.7	186.2	193.7	176.8	186.4	191.0	128.4	138.0	148.6	150.9	153.4	133.9	128.4	138.0	148.6	150.9	153.4	133.9
K_Q based on Maximum load with Graphical correction	188.5	200.1	204.2	183.5	191.6	196.4	140.9	147.5	154.6	156.1	158.0	137.1	140.9	147.5	154.6	156.1	158.0	137.1
K_Q as determined by Scaling correction	255.3	224.0	231.5	215.2	221.3	221.3	170.8	170.3	188.1	220.4	184.0	159.6	170.8	170.3	188.1	220.4	184.0	159.6

Note: Values are average of 3 or 4 tests

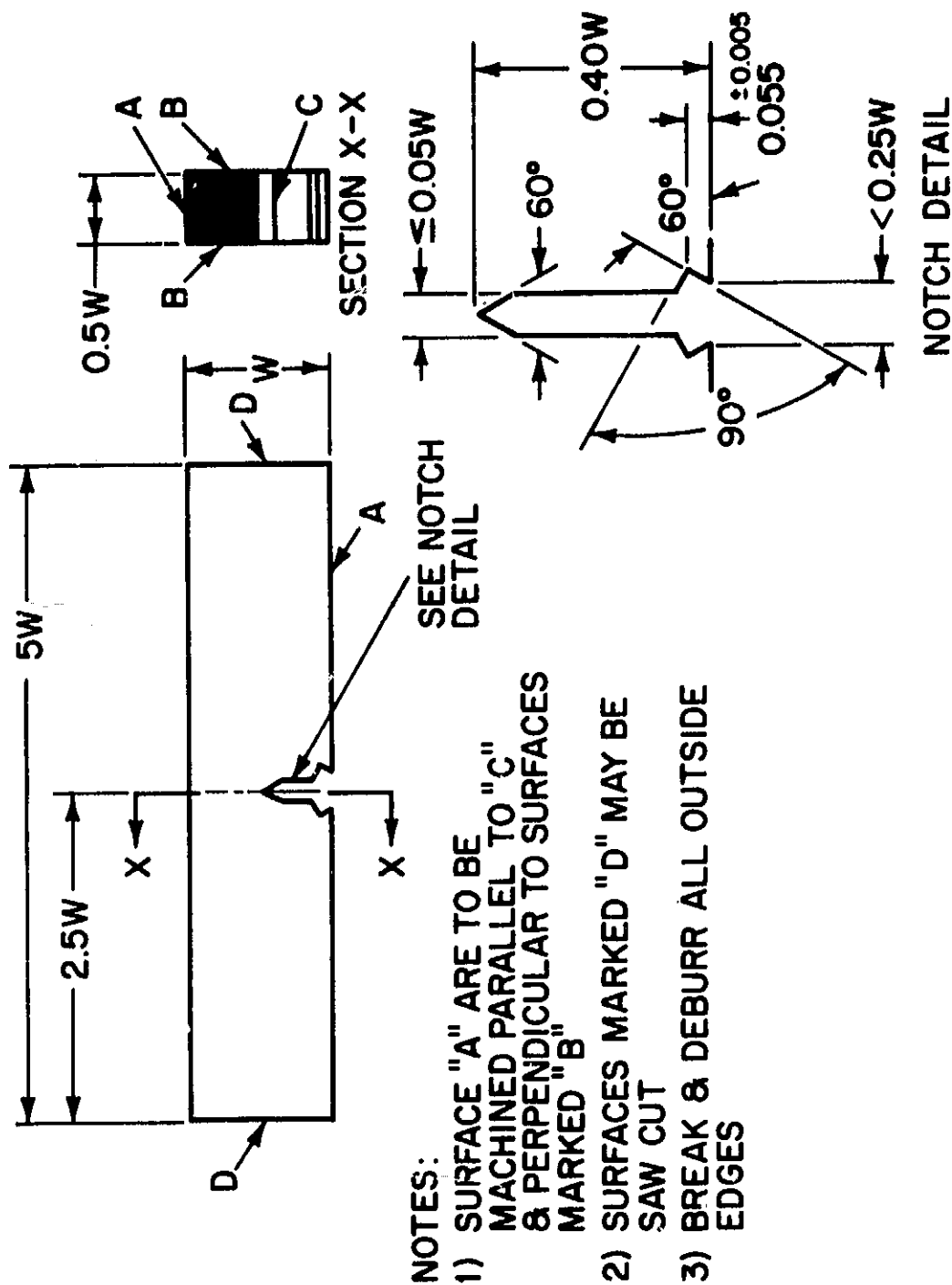
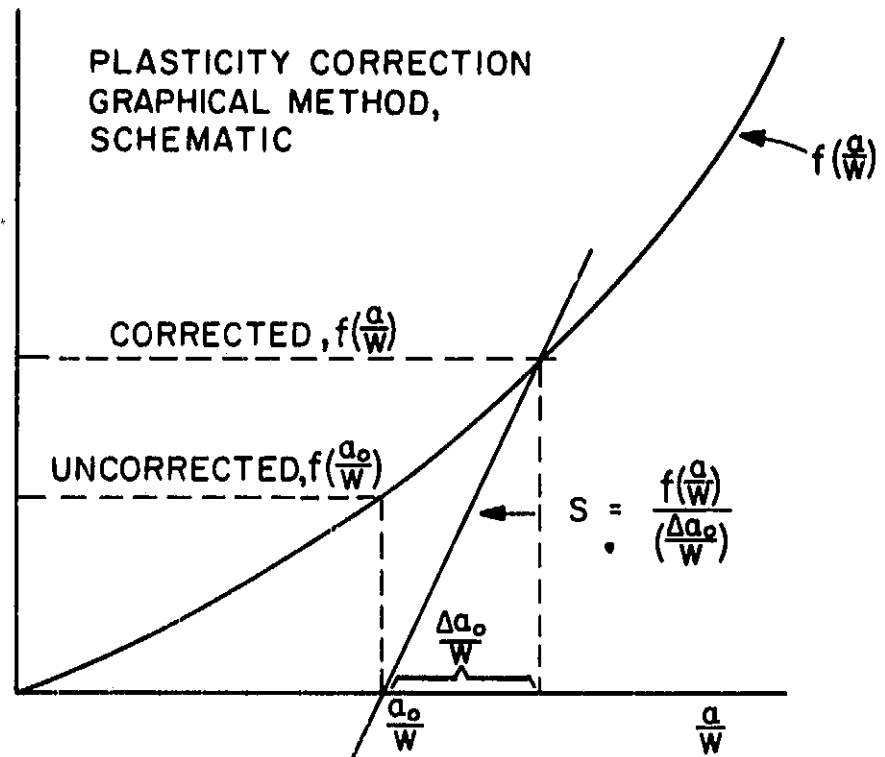


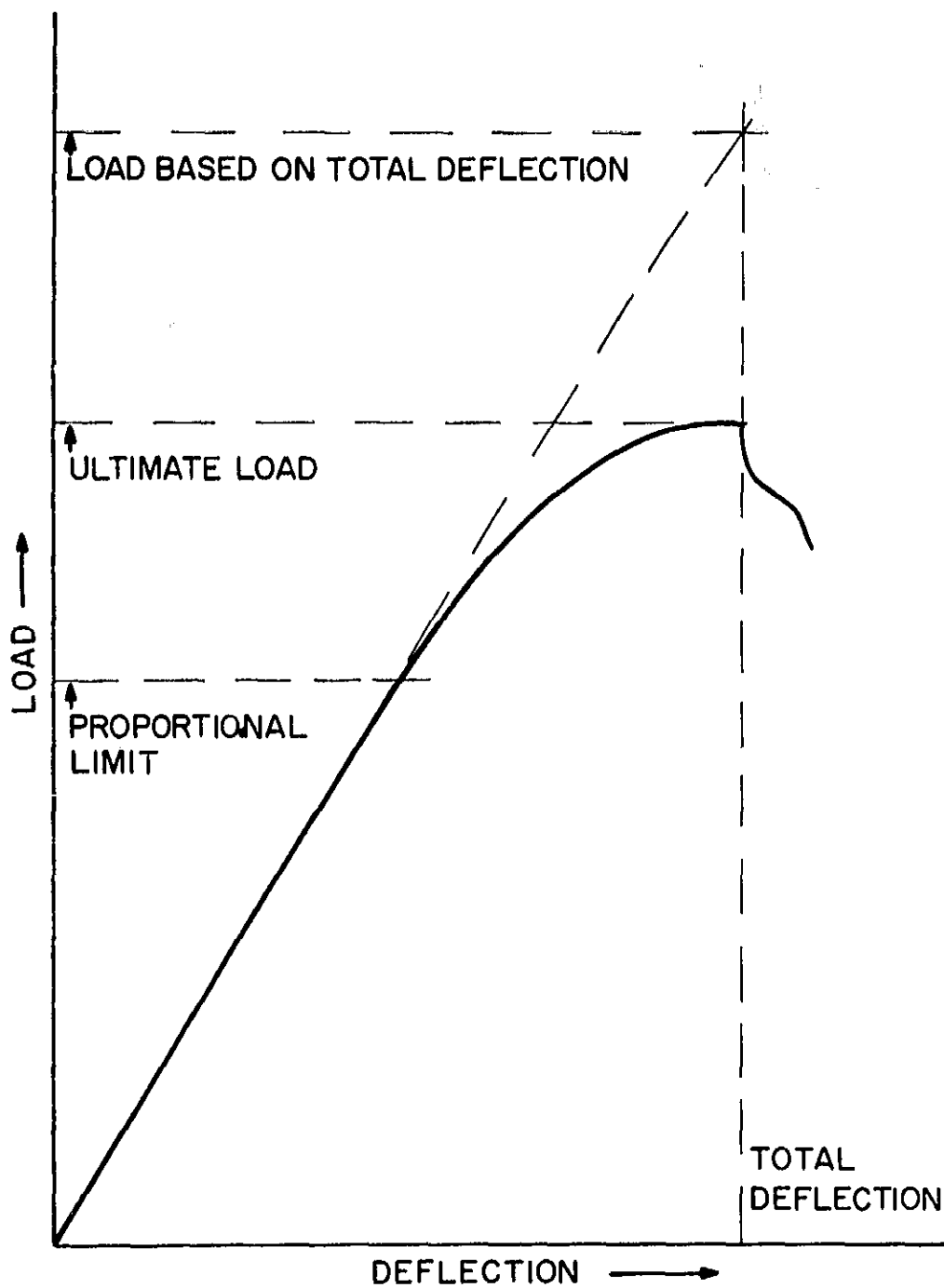
Fig. 1 - Fracture Toughness Bend Specimens

$$\frac{K_I^2}{\sigma^2 W} = f\left(\frac{a}{W}\right)$$



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Fig. 2 - Graphical Correction Method



LOAD-DEFLECTION CURVE FOR PRE-CRACKED
 K_{IC} BEND BAR SPECIMEN



Fig. 3 - Scaling Correction Method

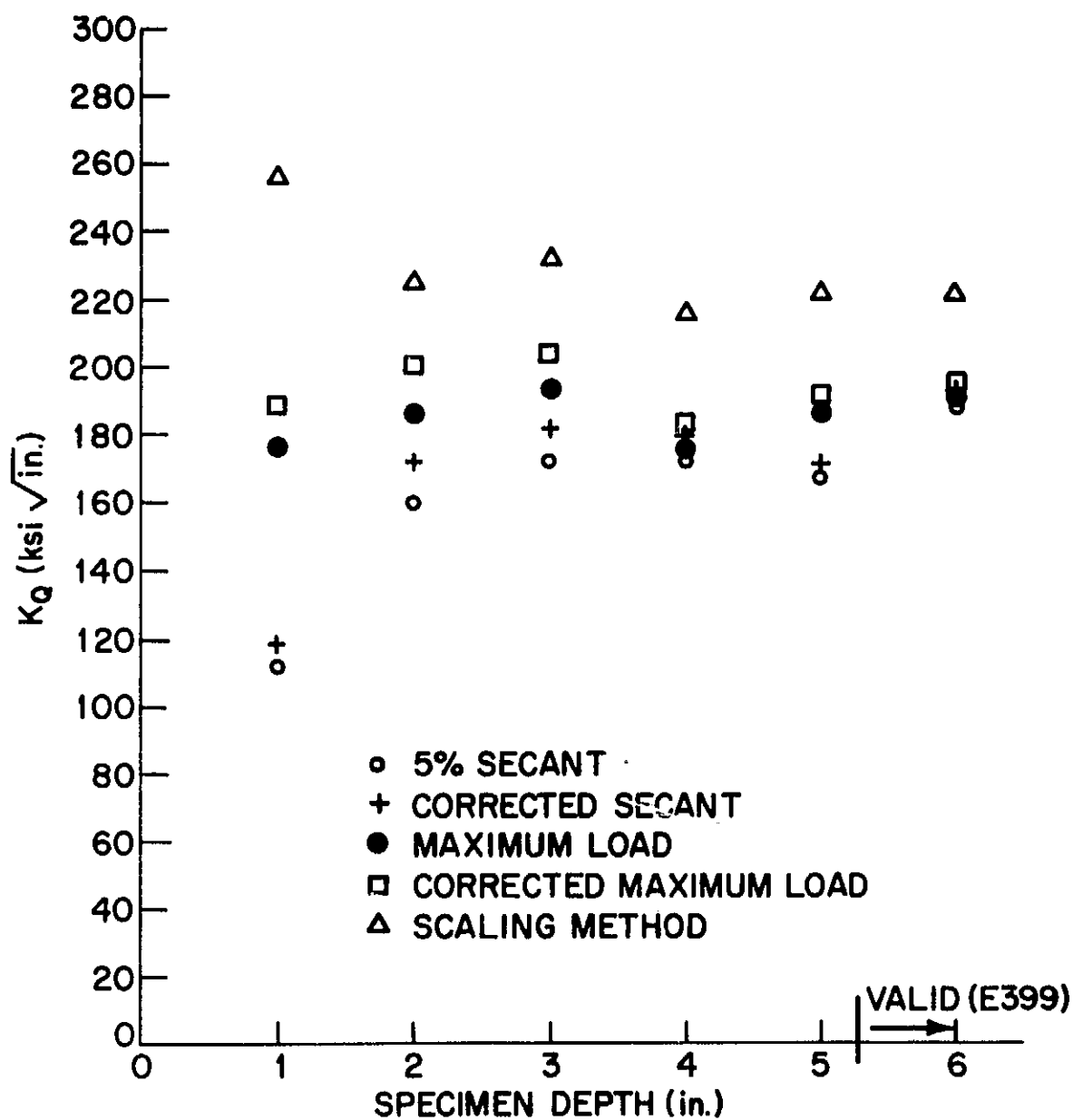


Fig. 4 - K_Q Values Calculated for 10% Ni Steel

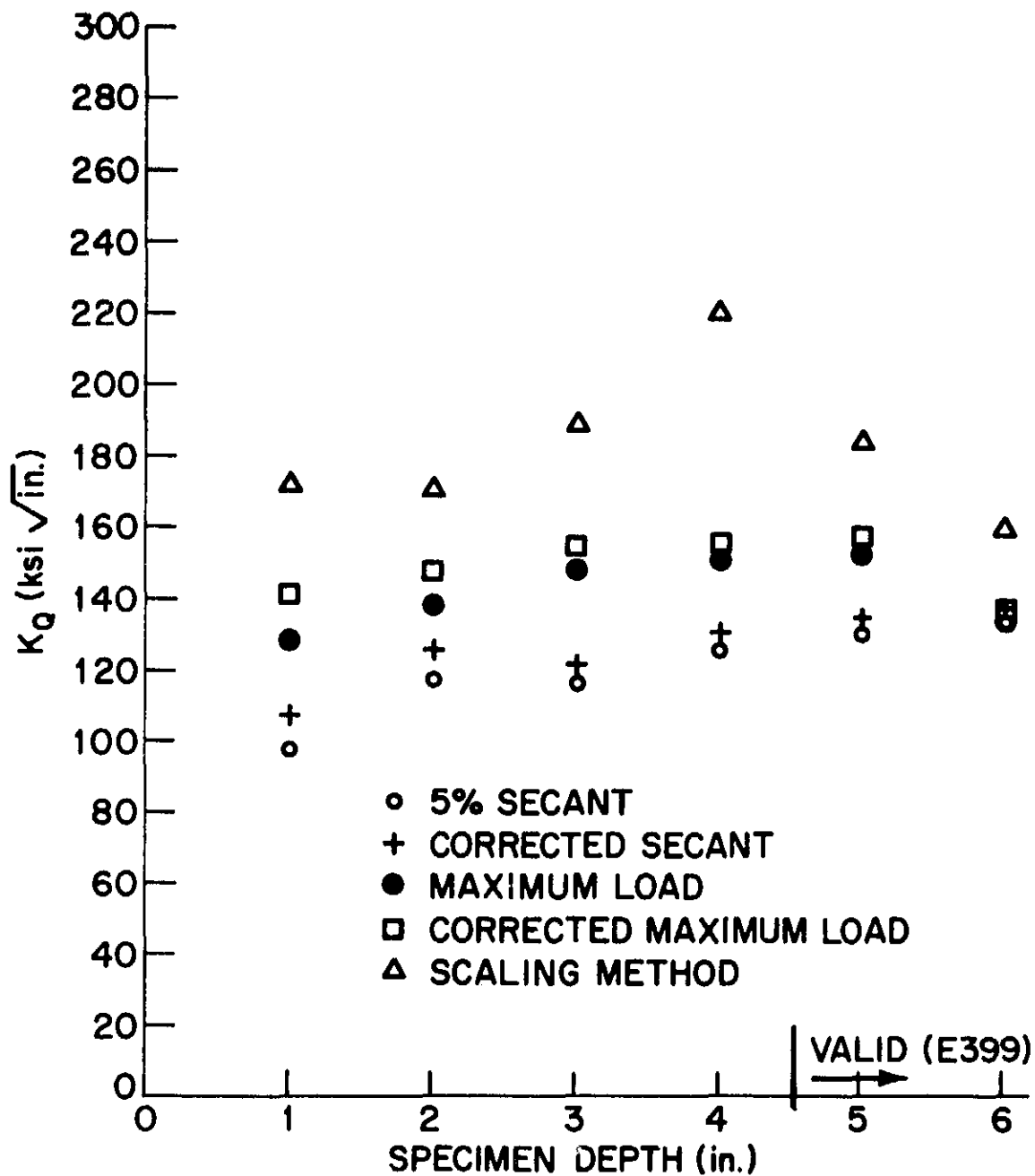


Fig. 5 - K_Q Values Calculated for 4340 Steel